LANSCE DIVISION RESEARCH REVIEW

Using SMARTS to Learn About the Peculiar Nature of Rocks Under Compressive Stress

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More than 80% of the volume of the Earth is solid rock, comprising the mantle and the important upper 30 km on which we live, the crust. Our knowledge of the Earth's interior comes from seismic data. With a correct model of the elastic and plastic behavior of the rocks as a function of position, observations of stress waves far from earthquakes and surface sources (such as nuclear explosions) enable us to pinpoint those sources and determine something of their nature. The "correctness" of the model determines the accuracy with which we can make these determinations, and is complicated by (among other things) the fact that the elasticity of most rocks changes with pressure *and* the immediate strain history of the rock. Rocks alter their elastic properties under strain changes, and "remember" the new state for some time before slowly recovering to their original state, or if the environment has changed, to a new state. For example, an aftershock following on the heels of an earthquake propagates through a *different* elastic medium than the main shock, but another shock a day later may travel through the original medium.

Curiously, the physical processes and origins of the odd memory effects shown by rocks are *not* known, much less incorporated into seismic models. To find and understand the origin of these bulk effects, we must study the corresponding behavior at the microscale of grains and bonds. Rocks are mineral aggregates—complex materials, and their responses at smaller scales may also shed light on other complex materials studied by the solid-state physics community, and be of interest to others who study material properties, such as the strength of concretes.

A single quartz grain behaves like a small spring; yet, when several are cemented together to form a rock, the behavior of the entire rock is dramatically different from that of a spring. Why? Does the elastic behavior of the grain change because it Is "glued" to several neighbors? Or perhaps the behavior has more to do with the "glue" itself which holds the rock together, even though the glue is a *very* small part of the rock's bulk? We have used neutron diffraction on the spectrometer for materials research at temperature and stress (SMARTS) to learn about the physics that underlies the unusual behavior of rocks under stress. With neutron diffraction, we can learn about the elastic behavior of the *crystalline parts* of the rock while simultaneously watching the entire rock's behavior. What we have learned is that the crystalline parts (i.e., the grains) of the rock still behave like little elastic springs, even when cemented together in a rock. It is the bond system—less than 5% of the total volume of the rock for our samples—that is responsible for the material's anomalous behavior in an aggregate. To our knowledge, this is the first experiment performed that proves that the bond system is the culprit for all the odd elastic behavior observed in rock.

Previous Experiments and Modeling

Experiments performed to measure how much a spring compresses while applying increasingly larger (squeezing) forces result in a linear relation—Hooke's Law—between stress and strain. If the same kind of experiment is performed for three small cylinders of various rocks and plots for each are made—we plot the stress (force/unit area) vs strain (change in length/total length)—we get the graph in Figure 1. Only the purple curve, a Novaculite (a pure quartzite) looks (mostly) like a spring. The Berea (light blue) and Meule sandstone (green) curves are quite different. Both the Berea and Meule sandstone curves show that these rocks get stiffer as the compressive force is increased. Both show an initial, probably permanent, deformation from their starting points, and finally, both show banana-shaped loops after the initial deformation. Even though this behavior has been known since the turn of the last century,[1] the underlying physical cause(s) for this behavior is still *not* known.

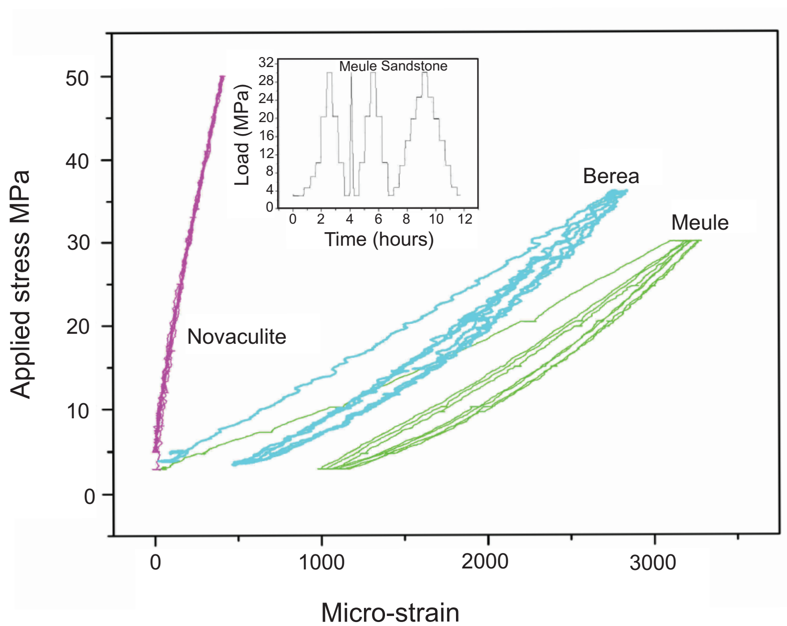

Figure 1. The macroscopic stress-strain response of a dense quartzite (Novaculite) and two porous sandstones. The novaculite is a good elastic material: the sandstones have unrecovered strain on the first compression followed by a crescent-shaped, repeating loop. ***The elastic response of these materials changes continuously with strain level.*** *The inset shows applied stress as a function of time, with plateaus when neutron data was accumulated.*

Models do exist which can *describe* behavior like this.[2,3] These models are simply made up of a collection of arbitrary, sticky "units." When the model "rock" is gradually squeezed, more and more of these little "units" stick together and, as a result, the "rock" gets stiffer. However, tell the model to stop squeezing, let go, and pull the "rock" apart and one of these typical units will eventually get unstuck but almost certainly not at the same point or in the same manner as it stuck together. As you might guess, these models are *purely phenomenological*. Identifying a real, physical mechanism is not necessary to make these models work, and that is *not* very satisfying. What *really* is going on at the micro- or nano-scale? Several mechanisms have been suggested: twinning and/or defect migration within the crystals themselves, phase transitions near stress-concentration areas, texture relaxations, time-dependent growth and healing of microcracks (i.e., Griffith cracks), or intergranular pressure solution changes—similar to what happens when an ice skate momentarily melts the ice under the skate because of the pressure above.

Our Experiments

Neutron diffraction on the SMARTS beam line at LANSCE has helped us begin to form a definitive answer to this question. Our initial results show how much of the strain deformation occurs in the quartz and how much appears in the grain-boundary and intergrain structure. Previous measurements have not allowed the integrated characterization that these neutron tools allow, so details of strain deformation is very poorly quantified (and mostly unknown) in rock mechanics. Neutrons are ideal probes in these types of studies because they can easily penetrate rocks and reveal properties of the bulk interior material, whereas x-rays, for example, can only measure near-surface regions.

Our experiments use SMARTS to observe, using neutrons, the *atomic plane strains* in the crystalline components of sandstones (and limestone and marble) to attempt to determine which components of the rock are responsible for the hysteretic behavior. Our samples are small cylinders (2.5 cm long by 1 cm in diameter) of Fontainebleau, Berea, and Meule sandstones. A white Arkansas Novaculite, a pure quartzite, was also chosen for comparison. Both Fontainebleau sandstone and the Novaculite are almost pure SiO_2. The sandstones are made up of almost all *crystalline* quartz grains. On the other hand, the Novaculite is much finer grained. Its density is also very nearly that of solid quartz—it has very little pore space. The samples were placed between the two anvils on the load frame (Figure 2), and a small extensometer, a device which measures strain, hangs below and is attached via rubber bands and two knife edges (not seen). A marble sample which has been fractured by the stress is shown.

Results

The plot in Figure 3 tells the story. The crystalline-lattice strains seen from the neutron-diffraction measurements for the three different sandstones and the Novaculite are plotted versus the applied external compressive load. There are no hysteresis loops or "bananas" present. The initial deformation doesn't show up here either. Essentially, the bulk crystalline elements of these rocks all behave like linear springs. Moreover, for the range of sandstones tested (from pure quartz to clayey quartz), the spring constant (slope) is nearly the same, meaning that the clays between the grains do not affect the grain's elasticity. It is also interesting to note that the Novaculite grains are somewhat stiffer here and look like what you would expect from a single crystal of quartz. The information contained in Figures 1 and 3 tells the story of how the strength, type, and size of the contact areas affect the macroscopic mechanical response of these quartz-bearing rocks. This set of experiments has also yielded data on calcite-bearing rocks which show behavior intermediate to the quartz rocks.[4]

Conclusion

What are the implications and conclusions of this work? We have measured and demonstrated for the first time that the actual grains of a rock are not the major players in the mechanical response of a rock, rather it is what is left, the bond and contact system and the stuff in between that is the cause of all the unusual behavior.[4] We have seen that the overall behavior looks similar in disparate rocks, but that the quantitative behavior, needed for models, depends on a combination of the porosity, the bond strength, and the bond geometry. These results direct us to look with a microscopic technique at the contact volume, to further explore the atomic-level contributions to the strength of complex geomaterials.

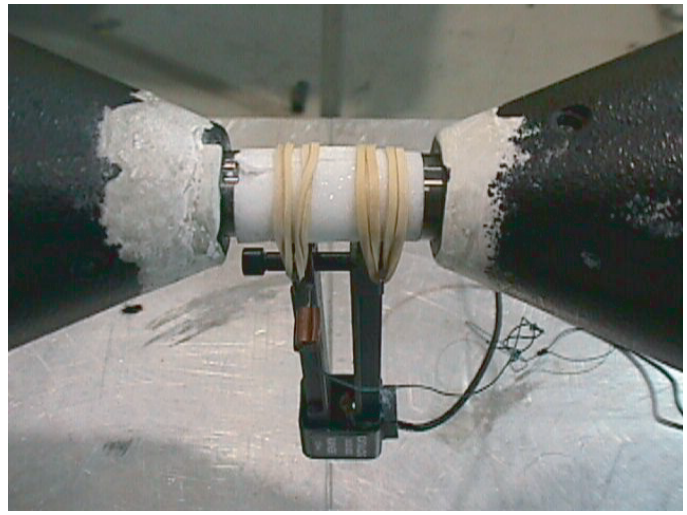

Figure 2. The breaking stress for the samples was determined by a destructive test. Here a Carrara marble sample fractures. The strain extensometer is still attached.

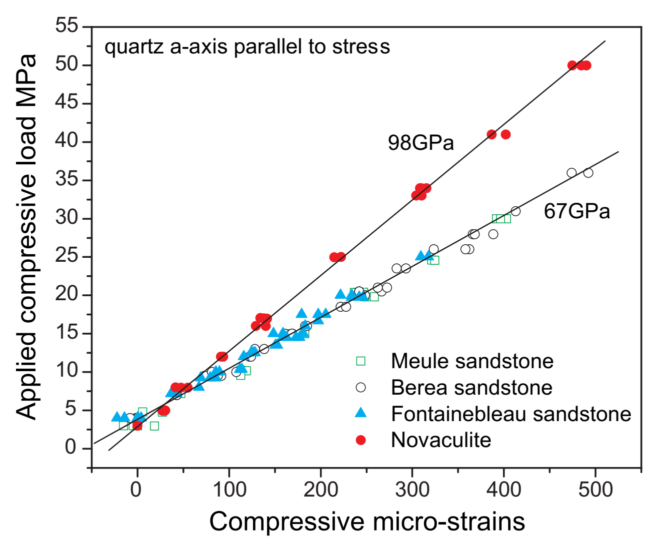

Figure 3. The response of the crystal lattice strain, measured simultaneously with the data in Figure 1. There are no loops or drifts—the bulk of the lattice responds linearly. The strain in the grains is essentially identical for all the sandstones and is much lower than the macroscopic strain (Figure 1).

Acknowledgments

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